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Degenerate electron gas effects in the modulation spectroscopy of pseudomorphic $Al_{0.32}Ga_{0.68}As/In_{0.15}Ga_{0.85}As/GaAs$ high electron mobility transistor structures

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The effects of a degenerate two-dimensional electron gas on the interband optical excitations, occurring in the active channel of $Al_{0.32}Ga_{0.68}As/In_{0.15}Ga_{0.85}As/GaAs$ high electron mobility transistor structures, were investigated by using phototransmittance spectroscopy. The ground state transition at room temperature exhibited a characteristic steplike line shape, which was considered to be an effect of the screening of excitons by the degenerate electron gas. A line shape fitting by using a first derivative of the absorption coefficient with respect to the electron sheet concentration n_s, allowed an estimation of the latter quantity by phototransmittance. An observed temperature-sensitive excitonlike signal, associated with the second electron subband was attributed to the modulation of the many-body correlation-enhanced excitonic absorption, known as the Fermi-edge singularity.

High electron mobility transistors (HEMTs), based on the AlGaAs/InGaAs/GaAs pseudomorphic (PM) heterostructure, have attracted considerable interest due to their performance in low-noise, high-power microwave applications, up to 94 GHz.[1] The high n-type doping of the AlGaAs layer and the large conduction band discontinuity between AlGaAs and InGaAs, produce a deep and narrow ($\sim$100 Å) nearly triangular potential well at the heterointerface. This results in a subband splitting[2,3] and a strong confinement of electrons so as to form a degenerate two-dimensional electron gas (2DEG) in the InGaAs channel.[2,3] Development of nondestructive methods (e.g., optical) is important to measure the sheet electron concentration n_s of the 2DEG in PM-HEMTs. Photoluminescence (PL) measurements at low temperatures have been used to estimate n_s.[2,4] Phototransmittance (photoreflectance), a contactless version of electromodulation spectroscopy,[5] also effective at room temperature, is an all-optical technique in which the transmittivity (reflectivity) is modulated by a laser light. Photoreflectance (PR) applied to HEMT structures has led to controversial results regarding the observation of a signal from degenerate 2DEG.[6–9] Conclusive evidence on the existence of a 2DEG signature has been given recently by Yin *et al.*[10] in PR and electroreflectance studies of $Ga_{0.78}Al_{0.22}As/In_{0.21}Ga_{0.79}As/GaAs$ modulation-doped quantum well (QW) structures. In that work,[10] only transitions to the higher ($n \geqslant 2$) electron subband states were reported.

In this letter, the ground state transition 11 h was observed at room temperature by phototransmittance (PT). The values of n_s, deduced from the fitting of the PT spectra, were in good agreement with data obtained by Hall measurements for two of the samples investigated. Finally, a signature from the Fermi edge singularity (FES)[11,12] at the 21 h transition energy was observed for the first time in modulation spectroscopy experiments.

Five samples were fabricated by molecular beam epitaxy on 2 in. semi-insulating GaAs (001) substrates. The general structure from the top free surface to the substrate was: (500 Å) n^+ 2.5×10^{18} cm^{-3} GaAs cap/(100 Å) undoped GaAs/(500 Å) undoped $Al_{0.32}Ga_{0.68}As/\delta$-doped layer/(thickness L_s) undoped $Al_{0.32}Ga_{0.68}As$ spacer/(130 Å) undoped $In_{0.15}Ga_{0.85}As$ channel/(0.8 μm) undoped buffer/semi-insulating (001) GaAs substrate. Structural parameters and Hall data obtained at 300 K are listed in Table I. PT measurements were performed by using a conventional experimental setup[13] in which the transmittivity T of the sample was modulated by a 0.95 mW He-Ne laser.

Room temperature PT spectra of four of the PM-HEMT structures with different n_s values are shown in Fig. 1. The spectrum of an undoped $Al_{0.32}Ga_{0.68}As/In_{0.15}Ga_{0.85}As$ heterostructure QW, used as a reference, with the same thickness (130 Å) of the InGaAs layer is also shown in Fig. 1. In all spectra, the signal at the lowest energy is assigned to the ground state transition 11h. Features at higher energies, denoted by A in Fig. 1, are associated with transitions to the second electron level $n=2$. Peak B at 1.39 eV, common to all spectra of the PM-HEMT structures, is considered to be a contribution from the GaAs layers and the GaAs substrate. Above this energy, the thick GaAs substrate is opaque, so that no PT signal can be obtained.

The 11h transition in the reference sample of Fig. 1 has an excitonic character with sharp positive and negative lobes in respect to the baseline. The same transition in the doped structures, exhibits distinctly different line shapes whose main characteristic is a unique steplike signal, more pronounced in S3. Also, it is worth noticing the lacking of negative lobes in samples S2 and S3. These unusual modulation spectroscopy line shapes can be understood in terms of the screening of excitons by the dense 2DEG, combined with conduction-band phase-space filling effects.[10] For interpretation of the data, a model is developed which assumes that the dominant contribution to the

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TABLE I. Experimental results for the sheet electron concentration n_s, electron chemical potential μ_e, and transition energy and broadening parameter E and Γ, respectively, of the ground state optical transition $11h$. μ_e is measured from the first $n=1$ electron level. L_s and $\delta-d$ are the spacer layer thickness and the planar doping, respectively. The experimental error in the PT measurements was determined by the resolution of the monochromator limited to 2 nm. The error given with the Hall data was estimated from the standard deviation of the measurement which was about 6%.

Sample	L_s (Å)	$\delta-d$ ($\times 10^{11}$ cm^{-2})	n_s($\times 10^{11}$ cm^{-2})		μ_e(meV)		E (eV)	Γ (meV)
			Hall	PT	Hall	PT		
S1	40	8.0	0.65(±0.04)	0.003	−58(±2)	−205	1.282(±0.003)	5(±3)
S2	40	13.0	5.4(±0.3)	5.2(±0.4)	+5(±2)	+4(±3)	1.274(±0.003)	5(±3)
S3	40	17.0	8.4(±0.5)	9.0(±0.6)	+23(±3)	+26(±3)	1.274(±0.003)	6(±3)
S4	60	25.0	14.0(±0.8)	19.4	+49(±4)	+71	1.275(±0.003)	9(±3)
S5	20	25.0	16.0(±1)	···	+57(±5)	···	···	···

changes $\Delta\alpha$ of the absorption coefficient α, comes from the modulation Δn_s of the sheet carrier concentration

$$\Delta T/T \simeq -L\Delta\alpha \simeq -L(\partial\alpha/\partial n_s)\Delta n_s, \tag{1}$$

where L is of the order of the InGaAs layer thickness ($\sim$100 Å). The dependence of α on n_s, is described by the widely used expression[10,14] $\alpha \simeq \alpha_0(1-f_e)$. By considering only band-to-band transitions with a broadened 2D joint density of states, the density independent absorption coefficient α_0, as a function of photon energy $\hbar\omega$, is given by

$$\alpha_c = I/\hbar\omega[\pi/2-\tan^{-1}(E-\hbar\omega/\Gamma)],$$

Lorentzian broadening (2)

$$= I/\hbar\omega[1-\mathrm{erf}(E-\hbar\omega/\sqrt{2}\Gamma)],$$

Gaussian broadening. (3)

Here, E and Γ are the transition energy and broadening parameter, respectively, and I is the intensity (oscillator strength) of the $11h$ optical excitation. The electron Fermi factor[10] $f_e(\hbar\omega,n_s)=(\exp\{\beta[\lambda_e(\hbar\omega-E)-\mu_e(n_s)]\}+1)^{-1}$ describes the dependence of α on n_s, through the electron chemical potential $\mu_e(n_s)$[11,12]

$$\mu_e(n_s)=1/\beta\ln[\exp(\beta\pi\hbar^2/m_e^* n_s)-1], \tag{4}$$

where $\beta=1/k_BT$, $\lambda_e=m_h^*/(m_h^*+m_e^*)$ and μ_e is measured from $E_1(n=1)$ level. The final expression is

$$\Delta T/T=\alpha_0(\hbar\omega)F(\hbar\omega,n_s)\Delta n_s, \tag{5}$$

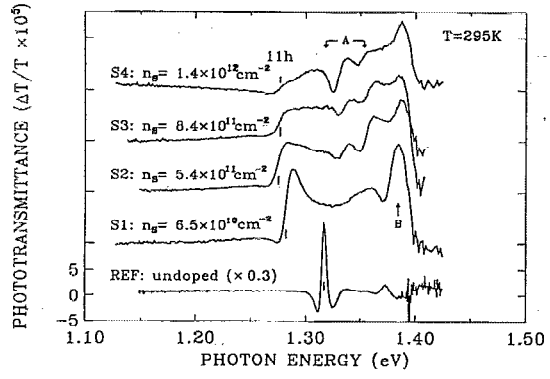

FIG. 1. Room temperature PT spectra of four HEMT structures with different values of the electron sheet concentration n_s. The spectrum of an undoped structure (REF) is also shown for comparison.

$$F(\hbar\omega,n_s)=L\beta\pi\hbar^2/m_e^*\{1+\exp[-\beta\mu_e(n_s)]\}$$
$$\times\exp\{\beta[\lambda_e(\hbar\omega-E)$$
$$-\mu_e(n_s)]\}/(\exp\{\beta[\lambda_e(\hbar\omega-E)$$
$$-\mu_e(n_s)]\}+1)^2. \tag{6}$$

The derivation of all of the above formulas will be given, in detail, elsewhere.[15] Equations (1)–(6) were used to fit the $11h$ experimental line shapes of the four PM-HEMT structures of Fig. 1, considering E, Γ, I, and μ_e as adjustable parameters. Electron and in-plane hole effective masses were taken[16] $m_e^*=0.064m_e$ and[2] $m_h^*=0.16m_e$, respectively. The fitting parameters listed in Table I, correspond to the Gaussian profile of Eq. (3), which gave better fitting results in comparison with the Lorentzian. Note that conversion from μ_e to n_s, and vice versa, is done by using Eq. (4). Regarding the samples S2 ($n_s=5.4\times10^{11}$ cm^{-2}) and S3 ($n_s=8.4\times10^{11}$ cm^{-2}), values of μ_e and n_s obtained from PT line shape fitting and Hall measurements agree within the experimental error. Values of n_s obtained from PT, are within 10% of those measured by Hall. In contrast, there is a large disagreement between PT and Hall data for structures S1 and S4 having the lowest and the highest n_s values, respectively. The disagreement in S1 may be explained considering that the 2DEG is not sufficiently dense to completely screen the exciton so that the model function of Eq. (5), in which only band-to-band transitions are included, is inadequate to describe the PT line shape. In S4, the anomalously large and broad negative lobe, is considered to be responsible for the limited success in fitting the $11h$ transition. It is emphasized here that contributions from other derivative terms in Eq. (1) are negligibly small,[15] making no improvement to the fitting results. In contrast to previous reports in undoped[13,17] and modulation-doped QW heterostructures,[10] where only terms $(\partial\alpha/\partial\Gamma)\Delta\Gamma$, $(\partial\alpha/\partial E)\Delta E$, and $(\partial\alpha/\partial I)\Delta I$ were considered, in this work modulation with respect to n_s gave the dominant effect.

The temperature dependence of the PT spectra of sample S4 ($n_s=1.4\times10^{12}$ cm^{-2}, at 4.2 K) is shown in Fig. 2(a). The 11 K PL spectrum of the same sample is shown in Fig. 2(b) for comparison. The assignment of the 1.348 and 1.404 eV PL peaks to the $11h$ and $21h$ recombinations, respectively, is well established in the literature.[2–4] According to a simple estimation $E_f-E_1\simeq(\pi\hbar^2/m_e^*)n_s=53.0$ meV, while from an inspection of the PL data of Fig. 2(b),

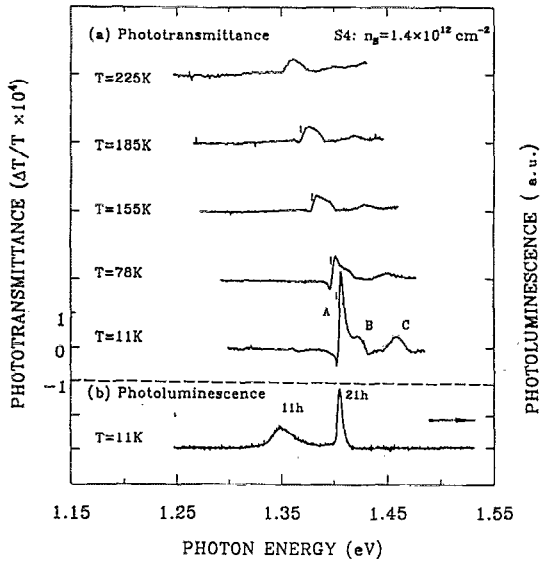

FIG. 2. (a) PT of sample S4 (n_s=1.4×10^{12} cm^{-2}) obtained at five different temperatures. (b) PL spectrum of S4 obtained at 11 K, corresponding to the scale on the right y axis.

$E_2-E_1\simeq 56$ meV, implying that E_f is only 3 meV below the $E_2(n=2)$ level. In this case the $n=2$ subband is populated at 11 K. In contrast to PL observations, the $11h$ transition could not be resolved in the low temperature PT spectra of Fig. 2(a) due to phase space filling which quenched absorption. In the high energy part of the spectra, peak C is associated with the $n=3$ electron level while a weak and broad feature, with a high energy tail denoted by B, is attributed to the $21h$ band-to-band transition.[10] Superimposed on B, a sharp and intense excitonlike feature A, consisting of a positive and a weaker negative lobe, dominates the 11 K PT spectrum at the $21h$ transition energy.

In our work it is known[5,13] that excitons dominate the electromodulation spectra of undoped QWs at all temperatures. However, in PM-HEMTs with a high value of n_s as in the case of S4, the appearance of an excitonlike PT signature at the $21h$ transition is not expected, since the single-electron-hole exciton is considered to be screened by the dense 2DEG. The temperature sensitivity is unexpectedly large, as seen from Fig. 2(a), where the intensity of feature A decreases rapidly with increasing temperature. This is in contrast with the behavior of peak B, the intensity of which remains constant as the temperature of the measurement changes. This behavior, is distinctly different from the one characterizing the excitonic PT and PR spectra of undoped QWs. In the latter case,[13,17,18] the intensity decreases in a much slower rate, and the exciton remains strong and well resolved up to room temperature, also confirmed by the 295 K spectrum of the reference (undoped) sample shown in Fig. 1.

Considering the difference of the well known behavior of the single-electron-hole exciton, it is proposed here that feature A in Fig. 2(a) originates from the modulation of a correlation-enhanced $21h$ excitonic absorption. The enhancement is due to the energy proximity of the $n=2$ state and the Fermi energy level,[3] which leads to a many-electron-hole Coulomb interaction, known as Mahan exciton.[19] The latter manifests itself as an enhanced absorption peak near the Fermi energy[11,12] (the FES) exhibiting an increased temperature sensitivity. This explains, at least qualitatively, the temperature dependence of the modulation absorption signal A in Fig. 2(a). Similar behavior of the $21h$ excitonic enhancement has been observed by Scolnick *et al.*[3] in PL-excitation experiments. In that work, for a sample where E_f was ~ 1 meV below the $n=2$ level (a situation resembling that in the present work) a decrease in the enhancement by a factor of 0.7 has been observed[3] from 2 to 40 K. This is to be compared with an estimated decrease of the PT signal intensity, by a factor of 0.3, from 11 to 78 K as seen from Fig. 2(a).

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[1] T. Mimura, in *Semiconductors and Semimetals*, edited by T. Ikoma (Academic, New York, 1990), Vol. 30.
[2] W. Chen, M. Fritze, W. Walecki, A. V. Nurmikko, D. Ackley, J. M. Hong, and L. L. Chang, Phys. Rev. B **45**, 8464 (1992).
[3] M. S. Skolnick, D. M. Whittaker, P. E. Simmonds, T. A. Fisher, M. K. Saker, J. M. Rorison, R. S. Smith, P. B. Kirby, and C. R. H. White, Phys. Rev. B **43**, 7354 (1991).
[4] J. M. Gilperez, J. L. Sanchez-Rojas, E. Munoz, E. Calleja, J. P. R. David, G. Hill, and J. Castagne, Appl. Phys. Lett. **61**, 1225 (1992).
[5] See for example, F. H. Pollak, Superlatt. Microstruct. **10**, 333 (1991); O. J. Glembocki, Proc. SPIE **1286**, 2 (1990).
[6] O. J. Glembocki, B. V. Shanabrook, N. Bottka, W. T. Beard, and J. Comas, Appl. Phys. Lett. **46**, 970 (1985).
[7] N. Bottka, D. K. Gaskill, R. S. Sillman, R. Henry, and R. Glosser, J. Electron. Mater. **17**, 161 (1988).
[8] N. Pan, X. L. Zheng, H. Hendriks, and J. Carter, J. Appl. Phys. **68**, 2355 (1990).
[9] M. Sydor, A. Badakhshan, J. R. Engholm, and D. A. Dale, Appl. Phys. Lett. **58**, 948 (1991).
[10] Y. Yin, H. Qiang, F. H. Pollak, D. C. Streit, and M. Wojtowicz, Appl. Phys. Lett. **61**, 1579 (1992).
[11] G. Livescu, D. A. B. Miller, D. S. Chemla, M. Ramaswamy, T. Y. Chang, N. Sauer, A. G. Gossard, and J. H. English, IEEE J. Quantum Electron. **QE-24**, 1677 (1988).
[12] See, e.g., R. Cingolani and K. Ploog, Adv. Phys. **40**, 535 (1991).
[13] A. Dimoulas, J. Leng, K. P. Giapis, A. Georgakilas, C. Michelakis, and A. Christou, Phys. Rev. B **47**, 7198 (1993).
[14] D. S. Chemla, I. Bar-Joseph, I. M. Kuo, T. Y. Chang, C. Klingshirn, G. Livescu, and D. A. B. Miller, IEEE J. Quantum Electron. **QE-24**, 1665 (1988).
[15] A. Dimoulas and K. Zekentes (unpublished).
[16] C. T. Liu, S. Y. Lin, D. C. Tsui, H. Lee, and D. Ackley, Appl. Phys. Lett. **53**, 2510 (1988).
[17] A. Dimoulas, K. P. Giapis, J. Leng, G. Halkias, K. Zekentes, and A. Christou, J. Appl. Phys. **72**, 1912 (1992).
[18] Y. S. Huang, H. Qiang, F. H. Pollak, G. D. Pettit, P. D. Kirchner, J. M. Woodall, H. Stragier, and L. B. Sorensen, J. Appl. Phys. **70**, 7537 (1991).
[19] G. D. Mahan, Phys. Rev. **153**, 882 (1967).